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Research and development on aspects of daylighting fundamentals

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ABSTRACT

The proper design and selection of daylighting systems can significantly help in improving energy efficiency and reducing environmental pollution. The aim of this paper is to review the fundamental aspects of daylighting and lighting control strategies, including the daylight factor, illuminance and luminance, and glare index. By itself, daylighting in a building does not lead to energy savings unless it is integrated with artificial lighting systems through lighting control techniques. The daylight factor is still the most commonly used parameter to characterize the daylight situation in a building. To achieve a comfortable brightness balance, it is desirable to limit the luminance ratio between areas of appreciable size as seen from a normal viewing position. The illuminance level and its distribution on the work plane and the surrounding area have a great impact on an occupant's visual task. Glare is recognized as an important issue in providing visual comfort and must be evaluated and prevented when it occurs within a daylit space. This work is a useful source for architects, building professionals, researchers, and newcomers to gain a better understanding of daylighting fundamental issues to promote effective daylighting designs and systems.

Contents

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1. Introduction

Daylighting is an important and useful strategy for accomplishing visual comfort, energy efficiency, and friendly building growth. Daylight is considered to be the best source of light for good color rendering, and its quality is the one light source that is the most probable equivalent of human visual response. Daylight offers a sense of cheeriness and brightness that has a significant impact on people [1]. The use of natural lighting is an important element in modern architecture as it aids in creating a pleasant visual environment. As an alternative to artificial lighting, daylighting offers a lighting source that most closely matches the human visual response. Daylighting provides a more pleasant and attractive indoor environment [2] because people desire good natural lighting in their living and working environments. It has been reported that good daylight conceivably improves the performance of occupants and contributes to a healthier working space [3].

People have become more conscious of the interaction between buildings, energy, and the environment. There has also been a growing concern among architects and building designers on the energy consumption in buildings and its likely adverse affect on the environment [4,5]. The efficient use of electricity can have economic and environmental benefits. Artificial lighting is one of the major sources of electricity consumption in many office buildings. In terms of economics, commercial buildings in the United States consume over one-third of the nation's primary energy, and artificial lighting is estimated to account for 25–40% of this energy consumption [6]. In Hong Kong, the electric lighting in office buildings is reported to be between 20% and 30% of the total electricity load [1]. Generally, the ranges of energy consumption greatly vary from country to country and are not only due to climatic conditions but also depend on cultural habits. Developed countries tend to present a higher lighting end-use [7]. Notably, energy savings in buildings will lead to not only financial savings and the reduction of the demand for electricity but also environmental benefits. The generation of electricity involving fuel combustion is associated with the production and emission of carbon dioxide (CO_2) and other gases into the atmosphere. This phenomenon, in turn, causes environmental pollution and global warming by the greenhouse effect [7].

Lighting energy savings may be obtained by either using more efficient lighting devices or increasing the natural lighting in the buildings. Using a lighting control system is a major component when daylight is integrated with artificial lighting systems. Significant energy savings in electric lighting, of over 30%, have been observed when high-frequency dimming controls are used [8]. Properly integrated daylight with artificial lighting systems through lighting controls can assist in reducing the electric lighting expenditure and peak electric demands [9]. Field measurements conducted on daylighting in a fully air-conditioned, daylit corridor have shown that energy savings in electric lighting are approximately 70% when a dimming lighting control system is used [3]. However, daylighting systems may often lead to high energy consumption in a building if they are not carefully integrated [10].

Large window areas may provide good amounts of daylight and pleasant views but can also allow large heat gains or losses, which will influence the energy consumption of the building. Daylight aids in decreasing the electricity use and the associated sensible cooling load due to artificial lighting. Therefore, proper daylighting designs can contribute to smaller air-conditioning systems and lower the peak power demand of buildings. Thus, the energy savings resulting from daylighting includes not only low electric lighting and reduced peak electrical demands but also reduced cooling loads and the potential for smaller HVAC systems [11].

Investigating the climate as well as the daylight availability at a construction site is a key aspect in understanding the operating conditions of the building's façade. Daylight availability data have been monitored every minute at more than 50 stations worldwide since 1991 [12]. Thus, there are several sources of information on daylight availability [13], including the U.S. Department of Energy, the National Renewable Energy Laboratory, and the Measurement and Instrumentation Data Center SOLPOS Calculator website [14].

Unfortunately, relatively few buildings actually integrate daylight with artificial lighting, and the information on the operational performance of these buildings is insufficient. Furthermore, surveys have indicated that daylighting strategies are not commonly incorporated in commercial buildings [3,6]. For instance, only 10% of US commercial buildings have some daylighting schemes, whereas almost 50% of the buildings are equipped with energy efficient lamps and ballasts [6]. The current paper will discuss some of the configuration issues in daylighting; this study aims to provide a broad overview of the suitability of daylighting strategies and its potential to save energy in buildings.

2. Daylighting and environmental pollution

A World Energy Council (WEC) study reported by Omer [15] found that without any change in our current practices, the world energy demand in 2020 would be 50–80% higher than the 1990 levels. The world's energy consumption by 2020 is estimated to be 53 billion kWh. Such an ever-increasing demand could place significant strains on the current energy infrastructure and potentially damage the world environmental health by CO, CO_2, SO_2, and NOx effluent gas emissions and global warming. Achieving the solutions to the environmental problems that we face today requires long-term potential actions for sustainable development. Population growth and economic development have led to an increase in the demand for energy, which is mainly obtained from fossil fuels [16]. According to Asif and Muneer [16], the global energy consumption is distributed as follows: 80% fossil fuel, 13.5% renewable energy, and 6.5% nuclear energy.

Buildings constitute approximately 40% of the world's annual energy consumption. Buildings mostly use electricity for the provisions of lighting, cooling, heating, and air conditioning [15]. Artificial lighting systems are major contributors to carbon dioxide emissions and global warming. These lighting systems consume approximately 25–40% of the annual energy consumption of buildings [6,17], which is about one third of the electricity bill [18]. The integration of daylighting with artificial lighting systems can potentially reduce the dependence on artificial lighting; this scheme is considered to be one of the simplest methods for improving the energy efficiency in buildings [9,19]. Such an approach would lead to reductions not only in energy consumption but also in environmental pollution [20].

Lancashir et al. [21] reported that each kWh of energy saved prevents the emission of 1.5 lb (680.39 g) of carbon dioxide, 0.20 oz (5.67 g) of sulfur dioxide, and 0.08 oz (2.27 g) of nitrogen oxide. Burton et al. [22] revealed that passive solar designs prevent the release of 162 million t/yr of carbon dioxide, 0.7 million t/yr of sulfur dioxide, and 0.2 million t/yr of nitrogen oxide. With the consideration of daylighting techniques, the annual savings in carbon dioxide emissions reached 192 million t in 2000; thus, 223 million t of carbon dioxide will be saved by 2010. McHugh et al. [23] reported that employing daylighting techniques in buildings that use skylights would reduce the energy demand in the United States by 24,000 MW. The energy saved by using daylighting is equivalent to 241,000 MW generated by nuclear power plants or 48,500 MW by fossil fuel power

plants. Daylighting can be applied at 1/20th of the cost of solar photovoltaic panels and generate the same energy savings. Daylighting in buildings could reduce the energy consumption of artificial lighting during daylight hours by less than 0.015 USD/kWh throughout the life of the building.

3. Daylighting

Daylighting can be grouped into seven main categories based on various purposes; namely, daylighting and environmental pollution, daylighting, illuminance, luminance, daylight factor (DF), daylight glare, and lighting controls techniques.

3.1. Daylight and daylighting systems

Baker et al. [24] defined daylight as "the combination of the diffused light from the sky and sunlight". In addition, Manning [25] indicated that "daylighting is any method by which natural light is brought into a room to replace or supplement artificial lighting." Light can come from many types of glazing configurations, which are either vertical or horizontal and from the side or from the top.

A daylighting system, as defined by Baker and Steemers [24], is "a device located near or in the openings of building envelope, whose primary function is to redirect a significant part of the incoming natural light flux to improve interior lighting conditions."

There are two simple daylighting systems, namely, side-lighting and top-lighting. Side-lighting, which is more commonly observed, is simply a window opening. Top-lighting is an opening in the ceiling or roof element of the building. The most common applications of top-lighting are the skylight, saw-tooth, and roof monitor.

Many daylighting systems have been developed over the past decades, and much information can be obtained from books and guides such as Crisp et al. [26], Monfardini et al. [27], Bell and Burt [28], Tregenza and Loe [29], and the Chartered Institution of Building Services Engineers (CIBSE) [30]. Littlefair [31] provided reviews on innovative daylighting systems that have been used in buildings; the author also provided guidance on daylight design.

3.2. Daylighting sources and availability

According to the Illuminating Engineering Society of North America (IESNA) Lighting Handbook [32], the sun is the source of natural light energy, and the path of the sun determines the available sunlight at a particular building location. The solar altitude and the solar azimuth are the two angles through which the position of the sun can be defined at a reference point on the surface of the earth. Overcast, clear, and partly cloudy skies are three light conditions to be considered in daylighting design.

In the overcast condition, the sky is generally the brightest element in an outdoor scene; the light reflected off of other surfaces has much lower luminance. Illuminance in the completely overcast condition can exceed 2500 fc. Partly cloudy skies are even more common, and there is constant change between direct sunlight and hazy daylight and fluctuations in intensity, distribution, and color temperature [33]. Under clear, sunny conditions, the sun is the brightest source of light and is practically a point source with coherent, parallel rays producing sharp shadows. The intensity of the sun varies with the thickness of the air mass through which light passes, which in turn is influenced by the altitude, solar altitude, and atmospheric conditions. The solar illumination at sea level can exceed 10,000 fc perpendicular to the sun rays [33].

The phrase "daylighting availability" refers to the amount of daylight available from the sun and the sky at a specific location, time, date, and sky condition [34]. The sun, sky, buildings, and ground are the main sources of luminance distribution. The latitude, climate, and building orientation affect daylight availability and thus must be studied in daylighting designs [35].

The daylight data and the equations derived from the data do not express the instantaneous values of illuminance and luminance; rather, they give mean values over time and measurement sessions. Thus, the measured instantaneous luminance may differ widely from those obtained from calculations based on the daylight availability [34]. Walkenhorst et al. [36] indicated that an accurate estimation of annual daylight availability is achieved by carrying out a series of daylight simulations for hourly or sub-hourly daylight conditions of the year. However, a complete yearlong run requires an extremely long time and extensive computation power, which inhibits its use by building designers for practical applications.

A new method has been proposed by Reinhart and Weissman [37] for testing the current and emerging daylight availability metrics such as the daylight factor, daylight autonomy, useful daylight illuminance, and LEED 3.0 requirements against the building occupant assessments of a daylit space. The method was tested as a classroom exercise by 60 architectural students in the 2nd floor studio space of le Corbusier's Carpenter Center in Cambridge, MA, USA. The results showed that the Lighting Measurement protocol for Spatial Daylight Autonomy, which is currently being developed by the Illuminating Engineering Society of North America (IESNA) Daylighting Metrics Committee, reproduced the student assessments of the daylit area in the room more reliably than the other tested daylight availability metrics. These results are preliminary and must still be validated and repeated in other spaces.

3.3. Daylighting design strategies

According to the definition of Ander [38], there are two simple daylighting design strategies, namely, side-lighting and top-lighting.

Side-lighting uses the walls of the building to admit daylight into interior spaces. It is a convenient strategy for a building, and provides both views and options for ventilation. Side-lighting provides light with a strong directionality, which diminishes as the distance from the aperture increases. In addition, this strategy is good for horizontal work plane surfaces. However, the disadvantage of sidelight is that it may cause glare, as the illuminating area is in the field of view of the occupants, and high contrast ratios often exist between the aperture and surrounding surfaces.

Top-lighting uses the upper part of the building element: the roof or another element above the ceiling line. The advantage of top-lighting is that it gives the designers flexibility in arranging the geometry and orientation of the daylight apertures according to the lighting needs of the occupants and it is not limited to wall orientations like side lighting [39]. Therefore, uniform light distributions are more easily achieved with top lighting. In addition, large quantities of light can be provided through relatively small openings.

Cohen et al. [40] reported on a passive solar design aimed to improve the energy efficiency of a single-storey primary school in Berkshire, England. Daylight was taken into account through windows and roof-lights. Although the artificial lighting system was manually controlled, daylight was predicted to provide 52% of the total lighting demand.

Cabus and Pereira [41] stated that although top-lighting can help reduce the electric energy used in artificial lighting, potential heat gains from inappropriate designs should also be avoided.

This challenge in designs with top-lighting must be examined closely, especially in buildings in low-latitude, hot and humid climates without a heating period. A study conducted by Zain-Ahmed et al. [42] demonstrated that energy savings of 10% could be achieved by using daylighting strategies in Malaysian buildings.

3.4. Daylight measurement

The International Commission on Illumination (CIE) designated 1991 as the ‘‘International Daylighting Measurement Year,’’ which was the first year of the ‘‘International Daylighting Measurement Programme (IMDP).’’ The objective of this program was for worldwide participants to measure the daylight availability parameters under a common set of guidelines [43]. The IDMP measuring stations have two categories, General Class, which principally measure illuminances and irradiances, and Research Class, which also record sky luminance distributions as well as other meteorological quantities.

Acquiring daylight illuminance and solar irradiance data is an essential stage in assessing the energy effectiveness of daylight in buildings. Long-term data measurement is recognized as a reliable and accurate method of setting up solar irradiance and daylight illuminance databases [44]. The recording practice for solar irradiance is obtaining the horizontal global and diffuse components, but the data often required in building design are those for vertical and inclined planes. In the absence of measurements, the luminous efficacy approach is the common method for estimating the horizontal irradiance and daylight illuminance and is used for investigating horizontal daylighting systems [45–47].

Chung [48] presented an experimental study of the luminous efficacy of daylight in Hong Kong. The daylight illuminance and solar irradiance were measured on a horizontal surface at intervals of one hour from December 1989 to March 1991. Statistical models have been developed to determine the luminous efficacy under different sky conditions, which enable the generation of daylight illuminance from available solar radiation data.

Li and Lam [49] indicated that the luminous efficacy models are established mainly for the horizontal surface, and very little work has been done for the vertical and inclined planes. The luminous efficacy relates to two important quantities, those of daylight illuminance and solar radiation.

For daylighting applications, the diffuse illuminance is more important and widely considered. The use of direct sunlight for providing natural light source in buildings is often excluded. Problems of glare, excessive brightness ratios, and visual discomfort support the exclusion. In addition, diffuse illuminance is more energy-efficient in terms of the luminous efficacy [50].

Littefair [51] analyzed the distribution of internal daylight illuminances to predict the annual lighting energy consumption in daylit buildings. The methods for computing this distribution were analyzed using new long-term daylight measurements in model rooms. The standard method results in large errors for certain window orientations, and alternative procedures have been examined as the basis for more accurate methods for predicting the lighting use in daylit buildings. Wong and Jan [52] used methods ranging from walk-through visual inspections to sophisticated instrumentation such as sensors and continuous data logging to analyze the existing lighting conditions inside classrooms.

Since the launch of the IDMP by the Commission Internationale de l'Eclairage (CIE) in 1991, the measurement of daylight illuminance has been undertaken and reported from various parts of the world [48,53]. The distribution of the luminance of the sky has also been recorded to obtain more data on the characteristics of daylight. A few stations with equipment that can measure the sky luminance have been erected in the subtropical region of Hong Kong. Some stations are closer to the tropics, such as those in Thailand and Singapore [54].

The daylight luminance distribution has been studied from measurements taken in high latitude locations such as European countries, as well as in North America and Japan. A number of luminance distribution models have been developed from these measurements, and some of these models have been adopted by the CIE as standard sky models [55].

4. Illuminance

According to IESNA [56], illumination (E) is defined as ‘‘the density of luminous flux on a surface; hence, it is flux divided by the area over which flux is distributed.’’ The unit of illumination is the foot-candle (ft-c). One foot-candle is the illumination produced on or at a surface, all points of which are at distance of 1 foot from a uniform point source of 1 candle.

4.1. Illuminance level (lux)

The illuminance and its distribution on the task area and its surrounding area have a great impact on how quickly, safely, and comfortably a person perceives and carries out a visual task CIBSE [57].

The Illuminating Engineering Society of North America (IESNA) [56] publishes recommended design illuminance levels at the work plane based on the task, occupant age, background reflectance, visual acuteness, and required accuracy. These recommendations are tailored to minimize electric lighting loads and are not designed to account for the intensity of sunlight. In daylighting applications, light levels of two or more times the IESNA recommendation are often acceptable to workers provided that the glare, relative brightness, and thermal comfort are adequately accounted for.

Several different illuminance recommendations for tasks are available, depending on the types of buildings and rooms. Table 1 shows the illuminance categories and recommendations for the illuminance values for the lighting in generic types of activities.

There is a large range of lighting conditions over which the human eye performs satisfactorily, as well as a large range of variation among individuals as to what comprises satisfactory visual conditions. Although there are no absolutely conclusive studies correlating the daylighting provision or occupant satisfaction with worker productivity, there is an increasing amount of evidence that the improper design of building parameters and room environments will lead to worker dissatisfaction, which may result in a reduction in worker productivity, and that glare-free and thermally-comfortable spaces have quantifiable influences on worker satisfaction and productivity [58,59].

The UK CIBSE Code for Interior Lighting recommends that offices should have a design illuminance level of 500 lx. A design illuminance of 500 lx is commonplace throughout much of the

Table 1
Illuminance categories and illuminance values for different types of activities recommended by IESNA [86].

Activity	Illuminance Category	Illuminance (Lux)
Visual tasks of high contrast or large size	D	200–300–500
Visual tasks of medium contrast or small size	E	500–750–1000
Visual tasks of low contrast or large size	F	1000–1500–2000

developed world. Consequently, electric lighting is usually designed to deliver 500 lx of (artificial) illuminance evenly across the work plane. When sufficient daylight is available, the electric lighting may be reduced, or switched off altogether, by either the occupants themselves or some control mechanisms.

The Cost-Effective Open-Plan Environment field study, conducted by the Institute for Research Construction (National Research Council, Canada) recorded that illuminances larger than or equal to 150 lx are classified as appreciable daylight [60]. Furthermore, the IESNA recommends 50–100 lx, provided directly onto the individual task area, as the general range of illuminance required for working with CRT screens in laboratory areas [61]. In addition, the Canadian Labor Code states that for task positions in offices where "continuous reading or writing is performed," the minimum illuminance shall not be less than 500 lx (approximately 50 foot candles). Based on these legal requirements, the daylight autonomy distribution at a workplace is defined as the percentage of the occupied times per year when the average desktop illuminance is above 500 lx [62]. Moreover, people have been observed to tolerate much lower illuminance levels of daylight than artificial light, particularly in diminishing daylight conditions at the end of the day. It is not unusual for people to continue reading a newspaper at levels as low as 50 lx, which is at least five times lower than the recommended artificial lighting levels for reading [63].

In a field study by Lawrence Berkeley National Laboratory (USA), office workers were allowed to create their own lighting environment by manually controlling the blade angles of automated venetian blinds and varying the intensity of the electric lighting. The control system was designed to adjust the venetian blinds to meet the design level with daylight (540 to 700 lx). The lighting systems were designed to supplement the daylight level to a design level of 510 lx if the daylight was insufficient. The study indicated that 75% of the workers in the automatic mode were comfortable with the overall lighting at an average illuminance of 593 lx, whereas 71% of the workers in the auto user control mode were comfortable with the overall lighting at 683 lx (13% higher). With the auto user control mode, six out of 14 (43%) occupants were comfortable with the overall lighting at an average illuminance of 590 lx in the morning and 693 lx in the afternoon, whereas 4 out of 14 were comfortable but preferred either more daylight or a higher electric light average illuminance for this mode, which was 793 lx in the morning and 696 lx in the afternoon [58].

Studies related to the reactions of office workers to daylight and lighting signified that most office occupants prefer to work under some form of daylighting. The results of the current survey confirmed three common assertions about lighting: (1) most workers consider having a reasonable amount of daylight penetrating the office to be very important for their well-being in offices, (2) the preferred illuminance level of people varies greatly (100 to 600 lx), and (3) those people whose essential activity is working on the computer tend to choose low illuminances (100–300 lx) [63]. The results also noted that satisfaction with daylight is a complicated issue that depends on many other factors, such as façade orientation, obstructions, effectiveness of shading devices, and levels of daylight.

Researchers have noticed that lighting levels that are markedly higher than the typical design work plane illuminance level (e.g., 500 lx) are tolerated by the occupants unless there is glare or direct sun, in which case the occupants may opt to operate a shading device [64]. Observations made by Roache over several weeks suggested that the visual environment (i.e., facing a computer workstation sideways) is reasonably comfortable when the working plane illuminance is below 1800 lx [65]. In the same experiment, the target daylight illuminances values were used for the main run of the experiment (700 to 1800 lx). This range of daylight illuminance appears to be acceptable for both computer- and paper-oriented tasks.

For some countries, an absolute illuminance level is used in systematic evaluations. For other countries, particularly those dominated by cloudy sky conditions, DF, or the ratio between the illuminance measured indoors at a reference point (e.g., the work plane) and the outdoor global illuminance on an unobstructed horizontal surface are used as the measures of light quantity. Given the variability of available daylight from the sun and sky, daylighting systems are evaluated based on the quantity of illumination provided for a task over time. For office work that involves both paper- and computer-based tasks, the larger the number of hours per year a system is able to meet but does not grossly exceed the design illuminance level, the more successful the design, as determined by Ruck et al. [66].

Reinhart et al. [67] examined the integration between the control of blinds and electric control systems through the monitoring of private and two-person offices in Germany. The experiments were set up to collect data, which included direct and diffuse irradiance, indoor temperature, desktop illuminance, occupancy of offices, and blind occlusions. The lighting levels were automatically dimmed using a ceiling illuminance sensor to provide a minimum level of 400 lx on each desktop. The results showed that approximately 85% of activated electric lighting (switch-on) occurred when subjects arrived at their offices. In addition, the venetian blinds were fully retracted on 80% of the occasions when the electric lighting was activated.

The indoor illuminance level required by building standards and codes on the working plane varies widely among countries and depends on the activity levels [68]. Ihm et al. [69] studied the effect of the desired illuminance level on the performance of daylight control for various locations. A simplified analysis method was developed and validated to estimate the potential reduction in annual electrical lighting energy use for office buildings. As expected, the higher the required illuminance level, the lower the potential energy savings from daylighting. However, for large daylighting apertures, the same energy savings are achieved regardless of the illuminance set point.

Perez-Burgos et al. [70] presented the results of a study on daylight illuminance levels measured on horizontal and vertical surfaces under clear skies. The behavior of the daylight illumination in a specific area in Spain was analyzed to determine the characteristic values of this parameter in this geographical area. Then, a series of measurements of the global illuminance on a horizontal surface and on oriented vertical surfaces (N, S, E and W) were collected and analyzed. To obtain the illuminance on a vertical surface, an empirical relationship was established with a high correlation coefficient and good statistical indicators. This methodology uses an uncomplicated parametric expression that considers all of the orientations of the vertical surface that are not directly illuminated by the sun. If the measurements of the horizontal illuminance are not available, it can be calculated from the horizontal irradiance by a luminous efficacy model.

In the past year, an empirical study by Lim et al. [71] of daylighting performance was conducted for an existing representative government office building designed in Malaysia. Field measurements were conducted to obtain the external illuminance and the internal work plane illuminance level of a typical officer's southwest-facing room. The study demonstrated that the internal daylight level in the building was inadequate despite the abundance of external daylight available in the tropic regions, which can be as high as 130 klx. The study also demonstrated that a simple modification of the external shading device and glazing type could provide significant improvements in the quantity and quality of internal daylight.

Several methods have been used to estimate the daylight illuminance levels over the years. Three techniques can be used, namely, analytical formulas, computer simulations, and scale model studies [72]. Designers benefit from the scale model method because it can both predict and evaluate the visual impact of the system, and measure the light admitted.

4.2. Illuminance distribution and uniformity

The distribution of light within a space is critical to the comfort and productivity of the occupants. Forcing the eye to adapt too quickly to varied light intensities is not only distracting and stressful but also potentially damaging. The IES recommends minimizing variations in the illuminance levels throughout a space and has created guidelines to assist in evaluating the relative brightness. The illuminance variation across the immediate task should be kept to a minimum to avoid distracting the occupants and causing visual fatigue (Rea [56]). A variation between the task plane and the background can draw attention to the task of improving worker concentration. Accenting work areas is particularly applicable in task lighting applications but should be limited to between 1.5 and 3 times the background illuminance level to minimize visual fatigue.

The issues of light distribution are particularly important in daylighting applications because the recommended design intensities for electric light have been progressively lowered to minimize power consumption, further expanding the gap between natural sunlight and efficient artificial lighting. Integrating daylighting into the lighting strategy from the beginning of the design process is essential in creating an environment that effectively limits the intensity of the sunlight allowed into the space while providing a uniform and controllable light distribution (Rae [56]).

The uniformity of illuminance refers to the illuminance conditions on the task and the immediate surroundings. Usually, this feature does not apply to the whole working plane but rather to a series of defined task areas on the working plane. The illuminance uniformity is expressed as the ratio of minimum illuminance to the average illuminance on a surface. A higher value denotes a more uniform illuminance. The CIBSE recommends that the working plane illuminance should have a uniformity rate of not less than 0.8 [73]. As a result, a higher illuminance uniformity implies better visual comfort for the occupants. However, there are no specific guidelines for the illuminance uniformity for all facilities. Most of the recommended values are for working spaces such as office buildings. In many studies, the guidelines for a working plane are used to analyze the illuminance uniformity of a space.

Chou et al. [74] addressed the problem of achieving uniform illuminance conditions in the range of 0.30–0.37 in single-sided, daylight-illuminated classrooms, such as those commonly found in Taiwan. Other related research includes a study by Ho et al. [75], who investigated the feasibility of using sun-shadings of various configurations to minimize the lighting power costs and enhance the daylight illumination of subtropical classrooms lit from a single side. The results showed that, given an appropriate geometrical configuration and suitable physical dimensions, sun shadings can improve the illuminance uniformity ratio from the usual range of 0.25–0.35 to the range of 0.40–0.42 in subtropical classrooms. Furthermore, sun shading with an optimal design not only improves illuminance uniformity ratio within the classroom but also makes possible a 71.5% reduction in the lighting power cost.

The diversity of illuminance expresses changes in the illuminance across a larger space. It is a measure of the range of lighting in a space and is meant to limit the peaks and troughs in the levels of lighting seen by the users of that space. The diversity of illuminance is expressed as the ratio of the maximum illuminance to the minimum illuminance at any point in the working plane of the main area of a room or space and should not exceed 5:1 [73]. Most guidelines of diversity are focused on working places and museums. In many studies, the guideline for a working plane is used to analyze the illuminance diversity of a space. In general, achieving a uniform illumination distribution within the space is necessary in safeguarding the vision of the occupants.

5. Luminance

According to Smith [76], "luminance is a measure of the luminous flux that passes through or is emitted from unit area of a surface. It is an indicator of the brightness of a surface. Luminance is applied to both light sources and flat surfaces, where it indicates the reflectance of the flat surface. The SI unit of luminous flux is Lumen (lm) and is equal to the luminous flux through a unit solid angle (steradian) from a uniform point source of 1 candle, or the luminous flux received on a unit surface all points of which are unit distance from a uniform point source of 1 candle."

5.1. Luminance ratio

The luminance is the amount of light reflected from a surface in candela/m^2. Visual performance increases with increasing contrast, which is the difference in the luminance between the object being viewed and its immediate surroundings. Conversely, the difference between the average luminance of the visual field (task) and the remainder of the field of vision should be low to avoid the discomfort of large and rapid changes in eye adaptation levels. Contrast is desirable in the object of view but is undesirable in the wider surrounding field of view (Table 2) Stein and Reynolds [77].

To achieve a comfort brightness balance, it is desirable to limit the luminance ratios between areas of appreciable size as seen from a normal viewing position, as shown in Table 1. These ratios are recommended as maximums, and reductions are generally beneficial. Effective visual performance is entirely possible in environments with much higher ratios, but it is simply not as visually comfortable and may be fatiguing [77]. According to CIBSE, in healthcare facilities, high luminance ratios should be prevented in the patient's field of view [73].

For an office environment, luminances near each task and in other parts of the office interior within the field of view should be balanced with the task luminance. Large luminance contrasts reduce the contrast of the image and can reduce visibility and performance [73] and also cause transient adaptation problem. When moving from one level of luminance to another, the eyes have to adapt. Thus, people feel uncomfortable when there are significant differences in luminance.

The luminance ratio between two surfaces gives an idea of the relative brightness of the surfaces and is used to determine direct glare sources. The luminance ratios recommended by the IESNA

Table 2
Recommended luminance ratio according to CIBSE [57].

Description	Luminance ratio
Between the task and the adjacent surroundings.	1:3
Between the task and more remote lighter surfaces.	1: 10
Between luminaries and the surfaces adjacent to them.	20:1
Anywhere within the normal field of view.	40:1

are 3:1 or 1:3 between visual tasks (paper or screen) and adjacent surfaces and are 10:1 or 1:10 between the visual task and non-adjacent surfaces (IESNA Lighting Handbook 2000) [78].

6. Daylight factor (DF)

Conventionally, the illuminance from natural sources is often determined in terms of the daylight factor (DF), which is the ratio of the internal illuminance to the outdoor illuminance simultaneously available on a horizontal plane from the whole of an unobstructed overcast sky [79]. The measurement methods for daylight in interior spaces take into account three components: the light being reflected directly from the sky (diffuse scattered light), or the sky component (SC), the light that comes from external surfaces, or the external reflected component (ERC), and the light reflected from surfaces within the room, or the internally reflected component (IRC) (Fontoynont [80]). Therefore, the total DF penetrating the space is measured by the following formula.

In other words, the daylight factor is expressed as a percentage of the outdoor light under overcast skies that is available indoors. This ratio is called the daylight factor, which is represented by DF.

$$\mathrm{DF} = (\text{indoorilluminancefromdaylight})/(\text{outdoor illuminance}) \times 100\%$$

when a building is designed to rely on daylighting, a prime design concern is the DF. Table 3 shows the recommended DFs by Stein [77].

In relation to the recommended DF, the design criteria are often expressed in terms of the average daylight factor (DFave) as a way to evaluate the daylight in a space. The DFave is the most widely used tool because it can be found in many codes, guides, and regulations, as shown below. The British Standards Institution, BS 8206 Part 2, recommends a DFave value of at least 2%. The value states that if electric lighting is not normally used during daytime, the DFave should not be less than 5%, whereas if electric lighting is to be used throughout daytime, the DFave should not be less than 2% if a predominantly daylight-like appearance is wanted. According to the British Council for Offices Guide, a DFave from 2% to 5% is recommended for an office workplace. Moreover, a recommended DFave of 2% can be found in other codes and papers (CIBSE [73]; Saridar and Elkadi [81]).

A recent survey of office workers was conducted on daylight. Approximately 270 occupants of 16 buildings around Britain were questioned. The results indicated that their satisfaction with daylight was maximized with a DFave between 2% and 5%. Moreover, people were generally positive toward daylight. However, the responses showed that people were more likely to be dissatisfied with daylight when the design DFave was over 5%. At these high daylight levels, increased complaints of sun and sky glare emerged (Roche et al. [82]). Above DFave of 5%, the room is likely to experience thermal problems due to the strong daylight (Brotas and Wilson [83]).

Although the DFave is used in many countries, it has some limitations. First, direct sunlight is excluded from the DF calculation due to the overcast sky condition. This characterization is appropriate for predominantly cloudy climates; nevertheless, it should not be used in sunny climates (Brotas and Wilson [84]). Second, as noted in one study (Reinhart [85]), the credibility of the DF in judging the overall daylight situation in a given building is intrinsically limited. However, the DF has been widely accepted because of the simplicity of the calculation and its provision of an outline of whether the interior of a given building is dark or bright.

The traditional modes of daylighting analyses have changed little over the past 30 years or so. The DF approach, either using scale models or computer simulations, is still the most commonly used daylighting assessment technique, and there is much work to be done to demonstrate the advantages that dynamic lighting simulation can offer (Mardaljevic [86]).

A recent assessment of the daylight factor was carried out by A Chel et al. in 2010 for a skylight combined with a dome roof structure of a mud-house in New Delhi, India, based on the modifications in the model developed by CIBSE. The modified model determines the daylight factor for three different work planes at different vertical heights (h) from ground surface, i.e., at $h=0$ (the ground surface), 0.75 m and 1.5 m above the ground surface. The prediction of the modified model was found to be in good agreement with the experimentally observed inside illuminance data, on the basis of the root mean square percentage error (e) and correlation coefficient (r). The annual average daylight factors for large and small dome skylight rooms were determined to be 2.3% and 4.4%, respectively [87].

A recent study by Du et al. [88] investigated, under an overcast sky conditions, the relationship between the vertical daylight levels at atrium well walls and the average daylight factor levels in rooms; the study also investigated the impact of the well geometries, surface reflectance and facade design on the average daylight levels of the adjoining spaces in the atrium building. The daylight levels in the rooms and on the walls were derived from scale model measurements, theoretical calculations and predictions from the lighting simulation software Radiance. The data from the Radiance program simulations show a good agreement with the measurements from the scale model studies for the atrium models with a well index (WI) value of 1.75 and four-story rooms. The average daylight factor levels in the adjoining rooms had a linear relationship with the vertical daylight level at the center of the facade of each floor.

At present, the use of the manual method, which utilizes the DF coefficient and relates the internal daylight illuminance to the external horizontal diffuse illuminance, is widespread. This method is recommended by the CIE with the utilization of an overcast sky covered with dense clouds [89]. The DF calculated under this condition is a constant that corresponds to that type of sky. When applied to other types of sky, the calculated internal daylight illuminance values have little meaning because for clear skies, the DF value is dependent on the position of the sun and can vary by a factor of 5 [90].

7. Daylight glare

According to Lighting Handbook of the IESNA [78], glare is defined as "the sensation produced by luminance within the

Table 3
Recommended daylight factor according to Stein 1992 [68].

DF	Task
1.5–2.5%	Ordinary seeing tasks, such as reading, filling, and easy office work.
2.5–4.0%	Moderately difficult tasks, such as prolonged reading, stenographic work, normal machine tool work.
4.0–8.0%	Difficult, prolonged tasks, such as drafting, proofreading poor copy, fine machine works, and fine inspection.

visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility." The IESNA also recognizes glare as an important issue in providing visual comfort. Glare is categorized into discomfort glare, disability glare, and overhead glare. Discomfort and disability are the two most frequently encountered forms of glare (IESNA [78]).

Discomfort glare is the most common form of glare; however, its physiological causes are not well understood. "Discomfort glare is a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view" (Ruck et al. [66]). The occurrence of glare is usually distracting and irritating, but, if sustained for long periods, discomfort glare can cause eyestrain, headaches, and other problems. The size, luminance, and number of glare sources and the geometry of the sources in relation to the eye and task plane are all key factors in minimizing the potential for discomfort.

The second and more acute form of glare is disability glare, which partially or totally obstructs vision and causes severe discomfort. Disability glare occurs when the light scatters within the eye, typically during low light conditions when the contrast of the retinal image is already lessened. Although there are no models to accurately predict the incidences of disability glare, experts agree that the size of the area affected, relative brightness, and composite intensity of all glare sources within the field of view are important factors (Ruck et al. [66]).

Overhead or "reflected" glare is due to the bright reflections of the sun or light source off of polished or glossy surfaces. These reflected images may actually assist with tasks such as inspection of paint for defects; nevertheless, the benefits of reflected glare are limited and uncommon. Video display terminal (VDT) screens are particularly susceptible to reflected glare, complicating lighting design in high VDT-use spaces. Reflected glare can be mitigated by providing light from both sides of the task or by specifying fixtures with optical designs intended to minimize reflected lamp images (IESNA [78]). The IESNA recommends that the conditions when glare might occur, especially within a daylit space, must be evaluated and prevented.

Discomfort glare is caused by a high or non-uniform luminance distribution within the visual field or by the high contrasts of luminance between the glare source (window) and its surroundings. Many studies have demonstrated that discomfort glare depends on the position and size of the glare sources, as well as on the part of sky seen through the glare source [91].

When discomfort glare is present, the occupants may not notice any effect on their work performance at all. However, they may experience certain physiological symptoms, such as headaches, later on, which could be attributed to their glare exposure at work (Osterhaus [92]). When disability glare is present, the occupants usually notice an immediate reduction in their ability to see or perform a visual task. They may react by shifting their position or by utilizing any shading devices at their disposal, such as closing the blinds or curtains. Sometimes both types of glare are present simultaneously [92]. In such circumstances, separating the two effects from an assessment viewpoint can be difficult, as the current glare prediction methods utilize different formulae for each type.

7.1. Daylight glare index (DGI)

The daylight glare index (DGI) is a metric for evaluating lighting under daylight conditions. For daylit rooms, discomfort glare from daylight usually occurs when direct sunlight enters the room and illuminates an interior surface or when high luminance exterior surfaces, or the sky, are viewed from within. The DGI has long been studied [93,94], and the original form of discomfort glare constantly expressed by Hopkinson, the "Cornell" formula, is the most common form and used by EnergyPlus. This index, however, tends to overestimate the glare under real sky conditions and non-uniform window luminance.

Although DGI results are not yet conclusive, the DGI is reported in this study as a means to evaluate one aspect of glare that affects visual quality. According to Chauvel et al. [95], the appropriate index for an office should not exceed 22. Table 4 provides the values for glare regions and their related glare index.

In recent years, there has been an increasing amount of literature on discomfort glare from daylight, as it is becoming a common problem in many building environments. Osterhaus [92] reviewed and discussed the advantages and limitations of using existing glare indices for daylighting conditions. The study concluded that the available assessment and prediction methods are of limited practical use in daylit situations, and currently, there is no provision for integrated systems that combine daylighting and electric lighting. The paper also presented selected findings from a case study of daylit office environments, which identified a number of important design considerations. Furthermore, ensuring the detailed assessment and identification of appropriate shading and glare control devices for working environments is apparently critical, due to the complexity of the non-uniform luminance distribution of many shading devices.

The effect of the adaptation level and daylight glare on the lighting quality perception of office workers in open plan offices was investigated by Speed [96] to isolate the causes of dissatisfaction within a large open plan office environment. It was hypothesized that the adaptation level would have a significant influence on people's perceptions of their visual environment. Outcomes from laboratory-based research indicated that situations where the mean adaptation levels are greater than 30–40 cd/m^2 would be judged as bright and well lit. However, the outcomes from the post-occupancy evaluation studies disagreed with these findings. Mean adaptation levels exceeding 100 cd/m^2 were associated with conditions perceived to be dim, gloomy, and inadequately lit.

Bellia et al. [97] compared the evaluation index of daylight glare, DGI, with the results of the perceived daylight discomfort glare. The aims were to obtain useful elements to elucidate the limits and applicability of DGI and to note and define possible changes. The results indicated that the DGI values, calculated using the standard method, do not show a regular trend when some values of the lower window part luminance are changed. However, this trend was not confirmed by the experimental results, as demonstrated by the degree of discomfort glare values. Furthermore, the DGI, in many cases, provides discomfort glare values that are noticeably greater than those perceived in real situations. Other related research includes a study by Cantin et al. [98], who presented a method for assessing the daylighting quality based on metrics related to the illuminance, distribution, glare, and directivity based on an earlier publication about daylighting quality by Ruck [66]. The calculations were performed

Table 4
Glare regions and their related glare index, according to Chauvel et al [95].

Zone	Region	DGI
Discomfort zone	Intolerable	>28
	Just intolerable	28
	Uncomfortable	26
	Just uncomfortable	24
Comfort zone	Acceptable	22
	Just acceptable	20
	Noticeable	18
	Just perceptible	16

using the lighting simulation programs RADIANCE and DAYSIM for southwest- and northwest-oriented offices in the CDP building in Montreal, Canada. The results indicated that the following set of metrics is the most useful for assessing the daylighting quality of architectural spaces: the useful daylight illuminance (UDI), the daylight glare probability, and the vector/scalar illuminance ratio. The findings also suggested that the DF should be replaced by the UDI; further empirical research is needed to establish the appropriate criteria for acceptable luminance ratios for adequately daylit buildings.

A new method for evaluating the daylight glare, consisting of a standard monitoring protocol and advanced formulae for window luminance, adaptation luminance, and exterior luminance, as well as formulae for the solid angle, modified solid angle, and configuration factor of the window, was introduced by Nazzal [99]. The proposed method apparently yields sensible and consistent glare values when tested against the existing glare evaluation system of Chauvel. Additionally, the proposed method was coded into a small program to calculate the luminance values and was incorporated with Radiance to compute the daylight glare indices.

Furthermore, Nazzal et al. [100] conducted a survey in a daylit-computerized office in Istanbul to identify the factors contributing to the discomfort glare sensation and test the applicability of the New Daylight Glare Index (DGI_N) method. The study concluded that the major factor affecting the discomfort glare sensation is high source luminance, as indicated in the studies of Chauvel [95,101] and Velds [102]. The results of the survey suggested that light distribution and the presence of reflections correlate strongly with discomfort experience, and the DGI_N could be sufficiently predictive to serve as an aid in design due to its capacity to show a reasonable correlation with subjectively perceived discomfort.

Three years later, Nazzal and Masoto [103] carried out experiments in a daylit office environment in Japan to verify the usefulness of the new mathematical DGI_N method and to identify the factors influencing the discomfort glare experience. A slight positive correlation was found between the DBI_N and the subjective evaluation. Additionally, a high $L_{\text{adaptation}}$ value together with the small ratio of L_{window} to $L_{\text{adaptation}}$ was clearly experienced, which is sufficient to neutralize the effect of glare discomfort. However, subjective assessments are poor glare indicators and are unreliable in testing glare prediction methods.

Other related research included a study by Wienold [104], who investigated user perceptions of solar shading systems regarding glare using laboratory tests with subjects, to compare the results with existing glare rating equations and derive a new glare prediction model. The luminance distribution within the field of view was recorded using CCD camera-based luminance mapping technology. User assessments at two locations with more than 70 subjects under various daylighting conditions were performed to assess the existing glare models and provide a reliable database for the development of a new glare prediction model. The comparison of the results of user assessments with existing models clearly showed a great potential for improving the glare prediction models.

7.2. Glare control

A key, but often neglected, aspect of daylight harvesting is the control of glare from direct sunlight, especially when using side-lighting at northerly latitudes (above 45°). Glare is excessive luminance and/or excessive luminance ratios in the field of vision. There are two types of glare: direct or discomfort glare, and reflected glare or veiling glare (Stein et al. [77]). Direct glare results when the light source is in the field of vision, whereas veiling glare is caused by the reflection of a light source on a viewed surface.

To date, two widely used devices for glare control are venetian blinds and light shelves. The most difficulties experienced with automatic blinds are the result of frequent blind operation and poor coordination between lighting and blind controls. In the case of manual blinds, the behavior of the occupants has been shown to limit daylight admission. Blind occlusions depend on the preferences of the occupants and their perception for excessive glare and solar radiation; meanwhile, changes of blinds throughout a day are ignored (Rae [105]). Once the blinds are closed, they are rarely retracted again.

Venetian blinds reduce the daylight admission even when open; the transmission of diffuse daylight through conventional, fully opened venetian blind slants (arranged horizontally) is as low as 50% of the total incident daylight (Kischkoweit [106]). Conversely, sun penetration is a problem with light shelves and other horizontal shading devices, especially in the winter. The result is that daylight harvesting is impaired by the measures to control the glare.

Arnal et al. [107] recently presented a new extension of the luminous atmosphere controller that prevents glare caused by daylight from occurring in the room. Outdoor glare sources were detected by using a fisheye video camera fixed on the building envelope. A numerical method was then used to determine the areas of potential glare within the room, and define the operating limits on actuators to reject them. A simulation was carried out to illustrate the impact of glare rejection on the room controller.

Generally, careful design and selection of daylighting systems in the design process of buildings can significantly improve the energy, visual, and thermal performances, thus reducing the energy consumption. The availability and ease of use of building energy and daylighting simulation programs make them effective tools for enabling more energy efficient building development.

8. Lighting control techniques

Daylighting in a building by itself does not lead to energy savings. Energy is saved by dimming the lights or switching off the electric system. Thus, the implementation of effective lighting control systems has become a major target for the reduction of the energy demand because it could assist in reducing the electricity consumption of a building.

8.1. Types of lighting controls

According to IESNA [78], two different types of daylighting controls are generally utilized to reduce the electrical lighting used in buildings, namely:

1. Continuous dimming controls: In this case, the artificial lights are dimmed or brightened in response to sunlight to maintain the set indoor illuminance level. A sensor, which is located at the station point, reads the exterior illuminance; if the exterior illuminance is greater than the target illuminance, then the artificial lights are dimmed, and vice versa. Thus, daylight responsive dimming systems are controlled by photosensors that adjust the electric lighting level according to the amount of daylighting on the photosensor. These systems are more expensive as they require special lamps and ballasts and more elaborate controls. Moreover, these systems are best suited for daylighting applications. In addition, the results and savings achieved by these systems depend considerably on the sensor placement, hardware quality, and commissioning [108]. Furthermore, compared with the on/off control system, dimming

control systems generally increase energy savings and the comfort of the occupants, as well as extend lamp life [19].

2. Switching controls: Lighting loads are switched on and off. This switching can be done manually with a simple wall box switch, remotely via relays or switchable circuit breakers by control systems, or by occupancy sensors. Another way to achieve switched light levels is through light level switchable ballasts. Rather than switching between lamps, the light level switchable ballast can reduce the light from all lamps in the luminaire. However, the on/off system is limited in its reaction and operation. Another problem is the rapid switching on and off of lights when the daylight levels are fluctuating. This issue is not only frustrating for occupants but also reduces lamp life. To resolve these problems, various techniques have been developed to reduce the fluctuations when using time delays [108].

8.2. Lighting controls and energy efficiency

Electric lighting is one of the main energy consuming items in buildings. The appropriate use of energy-efficient lighting lamps with high frequency lighting control systems and the appropriate design of the daylighting system can reduce the electric energy consumption, enhance the visual comfort of users, and contribute to energy-efficient building designs [54]. Many studies have evaluated the impact of lighting control on the energy consumption in buildings. The following paragraphs will focus on the results of some of these studies.

Based on field measurements of daylighting in an air-conditioned office building in Hong Kong, Li [1] reported that an indoor illuminance of 500 lx under an on-off control can provide daylight for the north- and south-facing offices just under 20% and approximately 30% of the time, respectively. The author further noted that substantial lighting energy savings can be achieved using daylighting controls, and the maximum lighting load did not exceed 180 W. The savings were due primarily to the use of dimming controls and occupancy sensors during lunchtime, with a small savings from electronic ballasts.

Onaygil et al. [109] evaluated the energy savings via a daylight responsive lighting control system for an office building in Istanbul. They demonstrated that the energy savings obtained by a daylight responsive lighting control system indicated differences according to the months and seasons. The energy savings reached 20% in December but increased to 47% in June and July. When seasonal differences were taken into consideration, it was found that a 21% energy savings in the winter increased to 35% in the spring and 45% in the summer. The energy savings during clear days totaled 35% but decreased to 16% on overcast days when the daily weather conditions were taken into consideration. Interestingly, the energy savings during mixed days were approximately the same as those on clear days.

In addition, Li and Lam [3] conducted field measurements on daylighting for fully air-conditioned daylit corridors. The electric lighting load, brightness of the fluorescent luminaries, daylight illuminance levels, and room parameters affecting the daylighting design were recorded and analyzed. The results of their analysis showed that the energy savings in terms of the electric lighting were approximately 70% when using a dimming lighting control system.

Further studies on daylighting strategies and benefits for office building in Egypt were also conducted by El Mohaimen et al. [110]. The authors indicated that a lighting control strategy has a considerable effect on the performance of daylighting system as evidenced by the variation of the coefficient b (an indicator of the daylighting availability during building operating hours, which represents the percentage of time in a year that daylighting can provide the desired illuminance set-point level within the perimeter areas of the building). This variation provides an indication of the maximum possible savings of electrical lighting achievable by incorporating daylighting. For stepped controls, the potential savings in lighting energy use increase with the number of steps.

Li et al. [8] presented field measurements for a fully air-conditioned open plan office using a photoelectric dimming system. The electric lighting load, indoor illuminance levels, and daylight availability were measured and analyzed. The general features of the results, such as the electric lighting energy savings and the transmitted daylight illuminance in the forms of frequency distributions and cumulative frequency distributions, were presented. Their research indicated that energy savings in electric lighting were over 30% using high frequency dimming controls. The results from the study would be useful and applicable for other office spaces with similar buildings layouts and daylight linked with lighting control systems.

Although many studies presented lighting control to be highly beneficial in terms of savings in the electric lighting system, several studies have also demonstrated that there are some restrictions in applying lighting control systems. This aspect is related to the preferences of the building occupants and the practical applications of these systems.

Littlefair [111] reported that one of the problems with lighting control has been in terms of the user reactions to its operation. People do not like automatic controls that switch on lights when they could have been off under manual control. The study further reported that in spaces such as offices, classrooms, and residences, switching on should be done manually, even if a daylight-linked automatic switch-off is offered.

In the same study, Littlefair [111] found that a special problem with lighting control switches is the rapid switching on and off of lights when the daylight levels fluctuate around the switching illuminance. This condition can upset occupants and reduce lamp life. Photoelectric dimming controls, although more expensive and more complicated to install, should save more energy. However, problems with this system have also been reported. These include poor operation of the system when a single photocell controls a wide area of the building with different daylight levels in different locations and inappropriate control algorithms that cannot maintain the required illuminance for the working surface.

In their study, Ehrlich et al. [112] admitted that the use of photo-sensor-based lighting controls has been generally unreliable because of the considerable effort required to properly place and calibrate the photo-sensor system, and the unreliability of such control systems constitutes a significant market barrier that prevents the widespread acceptance of daylight dimming controls in commercial buildings.

Recently, a study by Li et al. [113] investigated the energy and lighting performances for energy-efficient fluorescent lamps associated with electronic ballasts and high frequency photoelectric dimming controls installed in a school building. The average illuminance level was determined to be 600 lx, which is 100 lx more than the recommended value, according to CIBSE. The findings indicate that the energy consumption was computed to be 1.04 kWh less than that expended by the existing T8 light fittings with conventional ballasts, leading to a 28% reduction in energy costs for the electric lighting in the workshop. Additional electric lighting energy saving of 770 kWh/year could be realized if the high frequency lighting controls dim the illuminance down to the recommended value.

Regarding the commissioning of lighting controls, in 1999, Littlefair reported that this practice is important mainly because if the system does not perform properly, not only will poor energy savings be achieved, but complaints from occupants, and ultimately, system disconnection, will also ensue.

Other important daylighting aspects and their relationship to energy savings and energy efficiency will be investigated by the authors in the near future.

9. Conclusion

The natural lighting is considered the best source of light for color rendering. Its quality makes it the best source that closely matches the human visual response. The proper design and selection of daylighting systems can greatly help in reducing not only artificial lighting use but also cooling energy consumption and, therefore, the potential for downsizing air-conditioning systems. The daylight factor is still the only commonly used parameter to characterize the daylight situation in a building. The illuminance level and its distribution on the work plane and its surrounding area have a great impact on how quickly, safely, and comfortably an occupant perceives and carries out a visual task. Glare is recognized as an important issue in providing visual comfort and must be evaluated and prevented when it occurs within a daylit space.

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